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STUDY OF PHYSICAL, SETTLING, AND THICKENING CHARACTERISTICS OF A SLUDGE

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Study of Physical, Settling, and Thickening Characteristics of a Sludge

by

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Summary

Tests were conducted to obtain the physical characteristics of sludge obtained from Nassau County's Bay Park sewage treatment plant, Long Island, New York. The settling characteristics of the sludge in seawater were determined by modified pipette analysis as a function of suspended solids concentration, salinity, and depth of settling. The sludge was subjected to tests to determine its thickening capability.

The bulk specific gravity of the sludge was determined. The specific gravity of the liquid phase was constant at 1.000 g/cc. For different samples the percentage solids by weight varied from .8 to 2.2 percent. The specific gravity of the solids varied from 1.53 to 1.62 g/cc with corresponding volatile solids from 70.3 to 61.4 percent. In a homogenous suspension of sludge the time required for 40% of the solids to settle varied inversely with the 4/3 power of the concentration of suspended solids. The settling time was independent of the settling height for a well dispersed suspension. The effect of varying the salinity from about 30 to 35 ppt was negligible. The effects of additives on the rate of thickening were generally slight or negative with the exception of alum. The maximum solids concentration obtainable in laboratory tests was 5.5%.

INTRODUCTION

The Coastal Pollution Branch of the Environmental Protection Agency's Pacific Northwest Environmental Research Laboratory is currently engaged in the implementation of a mathematical model[1] designed to predict the transport and deposition of waste material barged to sea for disposal. In anticipation of a test dump at sea, it is necessary to determine certain physical parameters of the material to be dumped. This investigation is primarily concerned with ascertaining the values of these parameters for sludge obtained from the Nassau County Bay Park Sewage Treatment Plant, Long Island, New York, a possible source of the waste material to be tested.

The objectives of this study can be divided into three separate catagories.

The first of these catagories is the determination of the physical characteristics of the sludge. This includes specific gravities of the various phases of the sludge and the percentage of total and volatile solids.

The second is the settling characteristics of the sludge in seawater. The effects that varying the suspended solids concentration and the seawater salinity had on these characteristics were also investigated. The ultimate goal being the ability to determine a single best settling velocity for sludge suspensions.

The third objective was added as the investigation proceeded as it became apparent that increasing the sludge solids concentration would be beneficial from the standpoint of implementing the model. Studies were initiated to determine the feasibility of obtaining a higher solids concentration by conditioning the sludge with various additives.

The quantitative values obtained for this investigation are valid only for the particular sludge tested. Qualitatively, the behavior of a similar sludge would be expected to be the same.

Apparatus and Procedure

The sludge received from the treatment plant was stored unpreserved at four degrees centigrade until needed.

Physical Characteristics

Specific gravities were determined by pycnometer methodology. The pycnometer was rinsed with distilled water and thoroughly dried and weighed before each use. The pycnometers were calibrated for volume at twenty degrees centigrade using distilled water (P = .998203 g/cc at 20°C)[2]. The pycnometer was filled to the appropriate level with distilled water and placed in an ultrasonic water bath for fifteen minutes to effect the removal of any air. It was then transferred to a constant temperature (19.9°C) water bath and allowed to equilibriate for fifteen minutes. The pycnometer was then removed from the water bath, dried and weighed on an analytical balance. The weight should be quickly determined after removing it from the water bath to minimize temperature changes. The observed thermal expansion of the liquid in the pyncometer accounted for a temperature rise of $\sim$ .1°C, therefore the temperature at the time of weighing was 20.0° $\pm$ .1° centigrade. The calibration of the pycnometer thus obtained was reproducible within $\pm$ .01% relative.

The specific gravity of the sludge was determined directly, in an analogous manner, with the exception of the ultrasonic bath. The bath was used for a short period of time to effect the removal of any large gas bubbles clinging to the sides of the pycnometer. Any effects dissolved gases had on the specific gravity of the sludge were felt to be a valid contribution, therefore no attempt was made to exclude these gases. Reproducibility for this determination was + .1% relative.

The specific gravity was also determined indirectly to verify the relationship

$$BSG = \frac{P_s P_l}{P_l X + P_s - P_s X} \qquad (1)$$

where BSG = bulk specific gravity
P_s = specific gravity of the solid phase
P_l = specific gravity of the liquid phase
X = fraction by weight of solids in the sludge

The specific gravity of the sludge solids was determined directly. The sample was prepared by thoroughly drying at 95°C, grinding with mortar and pestal till powdery and redrying. A portion of the fine powder was placed in a weighed pycnometer and reweighed. The sample was diluted to the proper level with distilled water. It was then treated in a manner analogous to the calibration trials. The specific gravity could then be calculated from

$$P_s = \frac{P_w (W_2 - W_1)}{P_w V + W_2 - W_3} \qquad (2)$$

where

P_s = specific gravity of the solids
P^s = specific gravity of the distilled water
V^w = volume of the pycnometer
W_1 = weight of the pycnometer
W_2 = weight of the pycnometer and solids
W_3 = weight of the pycnometer, solids, and distilled water.

Reproducibility of this determination was ± .1% relative.

The percentage of total solids by weight was obtained by drying a weighed sample of sludge at 95°C until constant weight was obtained. The percentage of volatile solids was obtained by ashing the sample at 500°C until constant weight was obtained. Reproducibility in both cases was ± 1% relative.

In order to determine the specific gravity of the liquid phase, the solids had to be separated. Filtration proved impractical due to the fast clogging of the filter. Centrifuging proved effective as did a flash distillation at reduced pressure. The difference between the two being that the former contains dissolved salts, while the latter does not. The specific gravity of the liquid phase could then be determined as previously described.

The salinity of the natural sea water used in the settling test was obtained directly from specific gravity measurements and a calibration curve prepared from data of Lyman and Fleming.[3] The accuracy of this method was ± .1 PPT absolute.

Settling Characteristics

The sludge used in the settling test was first passed through a ten mesh sieve to remove any gross sized material. The material removed was small in quantity and consisted of bits of aluminum foil, small pieces of wood, bits of leaves, etc. Removal of these substances was assumed to have a negligible effect on the settling characteristics of the sludge. Two settling tubes were used for the test, one 15 centimetres in diameter and 213 centimetres in height; the other 9.5 centimetres in diameter and 120 centimetres in height. The large size of the tube was necessary to keep the total sample volume withdrawn small relative to the volume of the settling tube. The bulk of the settling experiments were carried out in the larger sedimentation tube. The tubes were provided with fixed position side entrance ports in order to allow a sample to be withdrawn via syringe and needle.

The settling tube was filled to the desired height with natural sea water and allowed to equilibrate to room temperature. An aliquot of seawater from the tube was withdrawn for a salinity determination. The necessary quantity of sludge was added to give the desired suspended solids concentration and thoroughly dispersed using a plunger in the small tube and an electric pump in the large one. Care was taken not to introduce air into the suspension. This is necessary to prevent the sludge solids from attaching to air bubbles and floating to the surface.

After a sufficient period of mixing, multiple samples were withdrawn at depths of 95 and 180 centimetres in the larger tube; 50 and 100 centimetres in the smaller tube. The samples were analyzed for suspended solids to verify that thorough dispersion of the sludge solids had occurred and the sampling technique was reproducible. Physical observation of the sample withdrawal via syringe and needle revealed that the withdrawal tapped a nearly spherical zone around the tip of the needle.

The suspended solids concentration was determined gravimetrically using Millipore filters as described by Banse, et al.[4] The sample size analyzed was selected so that the amount of suspended solids contained in the initial sample withdrawn lay between 5 and 10 milligrams. Solids in excess of 10 milligrams would nearly completely clog the filter. The standard error in determining the solids weight on the filter was ± .2 milligrams. In order to minimize the relative effect of this absolute error on the solids determination, it was felt that the size of the sample should be at least large enough to contain 5 milligrams of solids.

Three pore sizes of 47 millimetre diameter Millapore filters were tested for their relative effectiveness for the gravimetric analysis. The suspended solids value determined for any given sample was identical within the expected error limits regardless of the filter size used. The .8 micrometre was superior to either the .22 or .45 micrometre due to its higher rate of filtration.

The settling tests were carried out varying the initial suspended solids concentration from approximately 25 to 200 mg/l for salinities of 28.9 and 35.0 parts per thousand. Samples were withdrawn from the side entrance ports at predetermined times over a period of about twenty four hours and analyzed for suspended solids. These tests were carried out at the ambient temperatures which were 24 $\pm$ 2° centigrade.

A graph was prepared for each run plotting the percentage of solids settled as a function of time. A curve was drawn through these points and the times for 20, 40 and 60 percent of the solids to settle were extrapolated. The difference in the values of t_{60} and t_{20} gives a quantitative value for the width of the curve, while t_{40} was used for making comparisons from one experimental trial to another. t_{40} was chosen because for this value the settling curves generally had a relatively high slope and represented more than 50 percent of the total solids that would ultimately settle over the entire 24 hour period.

Thickening Characteristics

Experiments to determine the normal rate of gravity thickening of sludge and the effects of various methods of conditioning on this rate were carried out in standard glass graduated cylinders of 500, 1000, and 2000 millilitres size. Solutions of alum, ferric chloride, hydrochloric acid, and sulfuric acid were prepared for use in these tests. Seawater, sodium chloride and calcium oxide were also used.

Identical graduated cylinders were filled with sludge and the standard solution added to give the desired concentration of the additive. The samples were then mixed for ten seconds with a plunger, and allowed to settle quiescently at room temperature. The interface between the relatively clear supernatant and the settling sludge solids (operationally defined as the sludge bed) was well defined. The volume occupied by the sludge bed was recorded as a function of time. At the termination of the trial, the bed was analyzed for percent solids composition. Assuming a direct relationship between the sludge bed volume and the percent solids concentration, it is possible to caculate the percent solids concentration for any volume the sludge bed occupies.

Results and Discussion

Physical Characteristics

The specific gravity of the liquid phase of the sludge was determined to be 1.000 ± .0005 g/cc and was uniform for all samples tested. A slight difference between the values obtained from the sample centrifuged and the sample flash distilled was noted. The difference was less than .0005 g/cc and therefore insignificant, but could be attributed to the dissolved salt present in the centrifuged sample.

The specific gravities of the solids were 1.53 ± .01 and 1.62 ± .01 g/cc for sludge samples received at two different times. The volatile solids contents for the two different samples were 70.3 ± .5% and 61.4 ± .5% respectively. A lower volatile solids content implies a higher mineral content, hence a larger value for the specific gravity of the solids.

The total solids concentration, as a percent of weight, was found to vary within each sample unless mixing of the sample was continued while withdrawing the aliquot to be analyzed. The values determined were 2.20% for the first sample received and an average of 1.15% for subsequent samples (range from 1.1 to 1.2%).

The bulk specific gravity of the sludge was determined and compared to the value calculated from equation 1. The results indicated that the equation would accurately predict this parameter.

Figure I illustrates the relationship between the percentage of solids and the bulk specific gravity of the sludge and shows that approximately 7 percent solids is needed for the bulk specific gravity of the sludge to approach the normal specific gravity range of seawater.

Settling Characteristics

The results of the settling test carried out by varying the initial suspended solids concentration and the withdrawal depth for a constant salinity (29.8 PPT) appear in Table I. The effect of increasing the salinity to 35.0 PPT was negligible in these settling tests. In every case ~ 30 percent of the solids remained in suspension after 24 hours.

A variance for t_{40} on the order of 20% was noted for duplicate runs. Since the mixing of the sludge with the seawater for the settling test was determined to be complete and uniform; the sampling technique accurate within better than five percent, other sources are felt to be responsible for the variance. Since no control was exercised on the ambient temperature or the initial amount of turbulence present in the

settling tubes, these are the probable sources of the variance. Krone[5] determined that for a sedimenting suspension of mud, the rate of deposition depends on the probability of flocculation directly. Since the rate of flocculation is dependent upon the initial suspended solids concentration, temperature, and internal shear (turbulence), variance can be expected if the latter two are not controlled.

From the work of other researchers[6-8] on the settling velocities of mud suspensions, it was expected that there would be a large increase in the settling velocity with an increase in the settling height. Owen[8] determined for an extreme case an increase in the settling velocity by a factor of ten for a corresponding increase of the settling height by a factor of two.

The values determined experimentally for the settling time of the sludge suspensions (Table I) were nearly identical regardless of the depth of withdrawal for a given initial suspended solids concentration. The significance of this observation is that if the settling times were converted to a settling velocity, the velocity for the 1.8 metre depth trial would be twice that of the .9 metre depth trial. This transformation is misleading. The actual experimental parameter being measured is the suspended solids concentration as a function of time; settling velocity is a parameter derived from this measurement and is only valid if the predictions that can be made from it are correct. In a suspension of nonflocculating discrete particles, this works well. However, in a flocculating suspension, the density, size and velocity of the sedimenting masses are undergoing constant change. The velocity a floc has attained at a given time can be much greater than indicated by the depth it has reached. There are two distinct though not totally separable processes occurring, flocculation and settling of these flocs. In a well mixed suspension of sludge solids ($p = \sim 1.6$ g/cc) the rate of flocculation is the limiting process for the speed a suspension will settle.

The process of flocculation depends on collision and adhesion of particles after collision. In a flocculating suspension there are three mechanisms by which collision can occur. These are Brownian motion, internal shear, and differential settling.[9]

The frequency of collision due to Brownian motion can be described by:

$$I = \frac{4kTn}{3\mu} \qquad (3)$$

where

I	=	frequency of collision
k	=	Boltzman's constant
T	=	absolute temperature

n = number of suspended particles per cubic centimeter
μ = viscosity of water.

In order for this mechanism to previal, n must be very large. At concentrations in the range that the settling test were carried out, the frequency of interparticle collision is on the order of one per hour per cubic centimetre. It is obvious that the contribution this mechanism makes to flocculation is insignificant.

Collision due to internal shearing, or turbulence, as derived by Smulschawski[10] can be expressed as

$$J_j = \frac{4}{3} n_i R_{ij}^3 G \qquad (4)$$

where

J_j = frequency of collision on j size particle.
n_i = number of i size particles ($i < j$).
R_{ij} = sum of the radii of i and j size particles
G = local velocity gradient.

In a suspension containing a large number of small particles and a small number of large particles, the large particles will appear to collect the smaller particles, growing larger in the process thereby further enhancing their collision rate. By equation 4, as the collision radius R_{ij} becomes larger, the frequency of collision increases with the cube of R_{ij}. Therfore in a suspension containing a larger number of small particles, flocculation due to internal shearing would initially occur slowly while R_{ij} is small, then as the particles grow in size the rate of flocculation will accelerate. The size attained by the flocs will necessarily be a function of n_i.

As the flocculation and settling of the suspension proceeds with time, n_i is correspondingly reduced and the maximum size attained by the flocs is also reduced. Through this feedback mechanism, the rate of flocculation decelerates once the large flocs are formed and settled.

Collision due to differential settling occurs as large particles settle through a suspension of smaller particles. The expression for this is[9]:

$$H = \pi E R_{ij}^2 V n_i \qquad (5)$$

where

H = frequency of collision due to differential settling.
E = capture coefficient
V = relative velocity between particles.

Fuchs[11] determined that E falls off rapidly as the ratio of R_i to R_j departs from one. This is to say that a collision will probably occur only if the size difference between the two particles is not too great.

The physical behavior of the suspensions during the settling test could be described and classified as follows. After mixing of the suspension was discontinued, some turbulence still existed. During the initial phase of this turbulence, no flocculation occurred as the shear stress exerted by the turbulence was greater than the adhesive forces between particles. A few large particles were visually detected descending, but a change in the concentration could not be detected indicating the amount of material to be small. A number of large discrete particles (up to .5 mm in size) were observed in random motion. Later examination of these solids revealed that they were somewhat fiberous material. Although the specific gravity of the solids was on the order of 1.5 g/cc, the fiberous material, being very porous, easily absorbs the ambient fluid and the effective (in situ) specific gravity will be somewhat less than that of the dry solids.

As the turbulence decays, adhesive forces between particles becomes greater than the shear stress caused by turbulence and flocculation commences. According to equation 4, conditions are ripe for rapid flocculation. The local velocity gradient is high and there are a number of large discrete particles to act as "seeds" providing large values for R_{ij}. The rapid appearance of large flocs can be visually confirmed during the settling tests. Initially, the flocs being formed are still in random motion due to the turbulence. As the flocs further increase in size and the turbulence decreases, motion becomes more gravitational dominated and results in a net descent of the flocs. With

an initial suspended solids concentration of 200 mg/l., the diameter of these flocs were on the order of 4 mm with corresponding settling velocities of 3 to 6 mm/second. The prominent feature of these flocs was their large void spaces. Flocs of this size and velocity set up countercurrent flows which further aids in keeping smaller flocs in suspension.

The period following the initial appearance of these large flocs is marked by a general decrease in the maximum size (and their respective settling velocities) attained by the flocs. This is a direct consequence of a reduction of n_i as time elapses.

Equations 4 and 5 predict that flocculation due to internal shear and differential settling will tend to create two distinct populations of flocs, a relatively large number of smaller flocs or particles and a relatively small number of large flocs. The large flocs have discrete settling velocities much greater than that of the small flocs. The total mass of the large flocs is much less than the total mass of the small flocs. Since initially the suspension was well dispersed, flocculation proceeds at the same rate at both the 90 and 180 centimetre depth. Providing that the process of flocculation controls the rate of settling, nearly identical percent of solids settled versus time curves (settling curves) should experimentally exist at both depths. Since any flocs formed at the 90 cm depth must descend through the 180 cm depth at a constant velocity, one would expect the settling curve to be shifted to a proportionally greater time. This shift would be small compared to the total time elapsed because the time required for the flocs to descend from 90 through 180 cm is relatively small compared to the total elapsed time.

Equations 4 and 5 state that the rate of flocculation is dependent upon n_i other parameters remaining constant. The effect of decreasing n_i (suspended solids concentration) is to reduce the rate of flocculation. This, in turn, reduces the rate at which R_{ij} can become large. The result of this, as illustrated by figures II and III, is to increase the sedimentation time and decrease the sedimentation rate. From the result in Table I, we can see that the difference between t_{60} and t_{20} increases as the initial suspended solids concentration decrease, indicating a decreasing sedimentation rate.

The logarithm of t_{40} when plotted as a function of the logarithms of the initial suspended solids concentration result in a linear relationship (Figure IV). From this it can be determined that t_{40} is inversely proportional to the initial suspended solids concentration raised to the 4/3 power. It can be concluded that the settling time is primarily a function of the flocculation process for sludge solids of $\sim$ 1.6 g/cc.

This relationship will predict the sedimentation rate of a suspension that is initially well dispersed within finite dimensions. In an ocean environment, we may find the conditions somewhat different than those created in the laboratory. If we assume that the waste plume upon dumping in the ocean initially dilutes and then statically maintains its dimensions, certain parallelisms can be drawn.

The sedimentation rates determined experimentally (Figure IV) would be descriptive of the behavior of the solids within the plume. Once the floc has formed and exited from the plume, its settling velocity remains constant. To predict the time for deposition of this floc on the ocean floor, we need to know the time required for exit from the plume, the velocity of the floc at the time of exit, and the depth from the plume to the ocean bottom. As stated previously, flocs formed at the onset of sedimentation are the largest and those formed subsequently are smaller, coupled with a corresponding decrease in velocity. Figure V illustrates this decrease in the settling velocity as a function of time as determined by physically timing the flocs for an initial suspended solids concentration of 197 mg/l. In the absence of turbulence severe enough to break the flocs into smaller and slower units, the total time for deposition on the ocean bottom will be a linear combination of the time required for formation of the flocs and their descent velocity.

$$t_d = t_f + h/V_f \qquad (6)$$

where

t_d = total time for bottom deposition
t_f = time for formation of floc and exit from the plume.
h = distance from plume to the ocean bottom.
V_f = velocity of floc at time of exit.

Extrapolating values for t_f and V_f from Figures II and V, applying equation 6, t_d for $h = 15.24$ metres can be calculated and appears in Table II. From a plot of t_d versus the time elapsed (Figure VI), the time for bottom depositions of any fraction of the suspended solids can then be extrapolated. In the particular case represented by Figure VI, the time for 40 percent of the solids to reach the bottom would be 140 minutes.

The value of t_d is dependent on the value of V_f to the extent of $\sim$ 80 percent. In order to obtain an accurate value for t_d, a method needs to be devised for determining the median settling velocity for discrete flocs exclusive of the time of formation of these flocs. In the absence of this information, it is still possible to calculate a value for t_d which will represent a maximum value for t_d. From Figure IV we can determine, for a given initial suspended solids concentration,

the time required for 40 percent of the solids to flocculate and descend to 180 centimetres. For this to occur the settling velocity of 40 percent of the flocs must be $\geq$ 180 centimetres/t_f.

Substituting into equation 6

$$t_d \leq t_f + ht_f/1.8 \text{ metres} \qquad (7)$$

The resulting range of values for t_d with h = 15.24 metres (50 feet) is 293 to 7570 minutes for initial suspended solids concentrations 200 to 20 mg/l respectively. Dividing the total depth (h + 1.8 metres) by t_d, a minimum settling velocity representing the minimum average settling velocity during the sedimentation period can be obtained. The same value can be obtained directly by dividing 1.8 metres by the elapsed time from Figure IV. The values thus calculated are .97 and .038 mm per second (.0032 and .00012 feet per second) for concentrations of 200 and 20 mg/l respectively.

Thickening Characteristics

There are generally four basic zones recognized in a gravity thickening process:[12] (1) a clarification zone at the top with a relatively clear supernatant, (2) a zone of settling characterized by a relatively constant settling rate, (3) a compression zone accompanied by a decreasing rate of settling, (4) a compaction zone where the settling rate is very slow. Kallskopf[13] determined that compaction of sludge ceases when the consolidation pressure of the sludge solids no longer is sufficient to overcome the build up of interstitial pore water pressure. In the case of light or filamentous sludge this equilibrium can be reached at low solids concentration of two to three percent.

Several generalizations about the behavior of the sludge obtained from the Bay Park treatment plant became apparent during the course of thickening experiments. The sludge flocculates and compacts without the aid of any additives. If the sludge has a low solids concentration ($< \sim$ 1.8% by weight), it will rapidly consolidate into a bed of approximately 1.8% solids and compacts only slowly thereafter. If the solids concentration is greater than 1.8%, compaction proceeds only slowly. Figure VII, curve 1, illustrates the rapid attainment of a decrease in the sludge bed volume from 100 to 40% corresponding to a change in solids concentration from 0.8 to 1.8%.

The effect of CaO on thickening (Figure VII) was minimal. Initially a slight improvement was observed but the advantage disappeared with time.

The effect of adding seawater or sodium chloride to a sludge of 2.2% solids (Figure VIII) was to decrease the rate of compaction. In curve 2 and 3, it is interesting to note the initial thirty hours where only slight compaction occurs which is followed by a twenty five hour period with an increased rate of compaction, which subsequently returns to a slow rate of compaction. The reason for this behavior is not clear. The maximum solids concentration after 160 hours was achieved by the control at 4%.

The addition of $FeCL_3 \cdot 6H_2O$ to sludge of 2.2% solids had a negative effect on compaction. For doses of 0, 50, and 400 mg/l (Figure IX) the final solids concentration after 284 hours was 5.1, 4.5, and 4.9 percent respectively. The effect of $FeCl_3$ on sludge with initial solids of 1.1% was also negative.

The addition of H_2SO_4 in small doses (up to 800 ppm) did not improve compaction. Addition of large quantities of H_2SO_4 ($\sim$ 2400 ppm) accompanied by minimum agitation slightly aided compaction initially, but after 240 hours showed no significant improvement over the control. If, after addition of the acid, the sludge was slowly stirred for thirty minutes, the compaction was significantly hindered from the beginning.

The sludges treated with alum exhibited behavior that significantly deviated from the control. Figure X graphically depicts the thickening of sludge with initial solids of 1.15%. Considerable hinderance was induced by treatment with 200 mg/l and to a lesser extent, 50 mg/l alum. The control and the sludge treated with 100 mg/l alum displayed the best rate of compaction reaching a solids concentration of 4.6% after 280 hours. In contrast to this behavior was sludge with initial solids of 1.78%. All of the samples treated with alum initially compacted better than the control (Figure XI). The samples treated with 300 and 150 mg/l alum had the greatest initial rate of compaction, but sharply reduced this rate after attaining a solids concentration of approximately 3%. The sample treated with 50 mg/l alum displayed the best overall behavior with an initial high rate of compaction which continued for the duration of the test at a decreasing rate. The sample treated with 25 mg/l displayed a favorable behavior, but not as good as the 50 mg/l dose.

The solids concentration of the supernatant for the preceeding thickening test was less than .2% for all tests. Providing storage capabilities are available at the Bay Park plant, an increase in sludge solids concentration could be realized by quiescent settling of sludge in the storage tanks. After a period of settling the supernatant could be returned to the plant for reprocessing while the sludge bed of increased solids concentration is barged to sea for disposal.

These behaviors suggest the following mechanisms for the thickening process. Flocculation of the sludge solids occur and the flocs readily settle into a bed where structural bridging occurs between flocs. At this point rapid thickening ceases. Without additive, this corresponds to 1.8% solids for the sludge examined. Additives to the sludge can alter the structure of the flocs formed, causing bulky less dense flocs or compact more dense flocs depending upon the nature of the additive, quantity of the additive, concentration of the solids, and nature of the solids. The formation of smaller, dense flocs enables the volume of the bed to be reduced to a greater degree before complete interaction (bridging) between flocs occurs.

Up to this point, flocs can be considered as having settled through the supernatant. Upon completion of intefloc briding, the process is analogous to squeezing out of liquid from the bed. This can be accomplished by either the floc bridging breaking down or the actual collapse of the flocs. The rate at which this can occur will be determined by the relative strengths of the bridging and the flocs as compared to the consolidation pressure.

The curves in Figure XI suggest that alum not only effects the size of the flocs, but also the strength of the interparticle bonds. Curves 3 and 4 show that initially the formation of smaller denser flocs resulted in a rapid decrease in volume, but then reached a point where further consolidation proceeded at a drastically reduced rate suggesting that the structure of the bed was stronger than that of the control at the same concentration. In contrast, the control (curve 1) shows an initial slow rate of consolidation, proceeding at an increasing rate, and continuing compaction so that after 225 hours the solids concentrations exceeded that of either 3 or 4. The sludge dosed with 50 mg/l (curve 5) alum represents an optimum combination of smaller flocs that can readily be compacted by the existing consolidation pressure.

The maximum solids attainable in laboratory tests was 5.5 percent after 500 hours of quiscent settling. After this period of time, no further increase in solids concentration could be detected.

The short term effect of diluting the sludge with seawater also showed dependence on initial solids concentration. After five hours of quiescent settling, sludge with initial solids of 1.80% and diluted with 0, 10, 25, and 50 percent seawater attained solids concentrations of 1.81, 1.63, 1.55, 1.75 percent respectively. The effect on the bulk specific gravity of the resulting sludge bed was more dramatic being 1.006, 1.007, 1.010, 1.014 g/cc respectively.

The effect of diluting sludge with initial concentration of 1.15% solids with 0, 10, 25, and 50 percent seawater was to produce a bed with 1.24, 1.75 2.11, and 2.45 precent solids respectively. The greater the dilution the less interference between flocs settling, hence they are able to consolidate in a bed of higher solids for a given period of time. The bulk specific gravity of the resulting sludge beds were 1.004, 1.007, 1.011, and 1.015 g/cc respectively. The change noted in the bulk specific gravity is due to the addition of large quantities of seawater (P = 1.020 g/cc) rather than the increase in percent solids.

Conclusions

The settling of solids is a function of the solids ($p = \sim 1.6$ g/cc) concentration for a flocculating suspension. The initial solids concentration not only affects the rate at which flocculation proceeds, but also the size of the flocs and hence their respective settling velocities. In an ocean dumping, the sedimentation process should be divided into two distinct phases: formation of the floc in the plume and settling of the floc through the water column. Pipette analysis of sedimentation rates yield only a partial picture. Further laboratory test under conditions modeling as closely as possible an ocean dumping situation in complete detail may yield a more accurate picture. In view of the difficulty in obtaining an accurate modeling, an empirical evaluation in the field may be more practical. The usefulness of pipette analysis should not be overlooked in establishing limiting values for sedimentation rates. In the consideration of minimizing or maximizing sedimentation rates (effective settling velocities), the effect of suspended solids concentration is well defined.

The effectiveness of additives on the thickening of processed sludge is limited. The use of alum in increase solids concentration is indicated in special cases depending upon the concentration of the solids and the length of time it can be allowed to settle. The best solids concentration obtainable after one week of settling was around 4 percent, a significant improvement. Seawater can be effectively used to increase the bulk specific gravity of the sludge, but the large amounts required make the desirability of handling the increase in volume versus the benefits derived questionable. Mechanical methods for the thickening of sludge should be considered.

ACKNOWLEDGEMENTS

I would like to thank the Western Interstate Commission for Higher Education for making this study possible. I would also like to express my gratitude to Walter Rittall, George Ditsworth and William Muellenhoff for their suggestions and help throughout the course of the project.

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Depth of withdrawal cm.	Initial suspended solids conc. mg/L	Approx. dilution for sludge of 2% solids	t_{20} min.	t_{60} min.	t_{40} min.
960	196	102	15	110	34
930	197	102	15	100	28
950	187	107	15	140	34
970	118	169	30	300	64
970	110	182	30	300	68
970	58	345	80	450	160
960	29	690	150	2000	450
1790	196	102	14	90	32
1770	197	102	17	110	33
1800	187	107	17	160	42
1820	118	169	33	300	70
1820	110	182	33	300	72
1820	58	345	80	450	160
1810	29	690	190	2000	500
830	147	136	20	178	4[illegible]
790	88	227	35	240	81
500	209	96	14	100	28

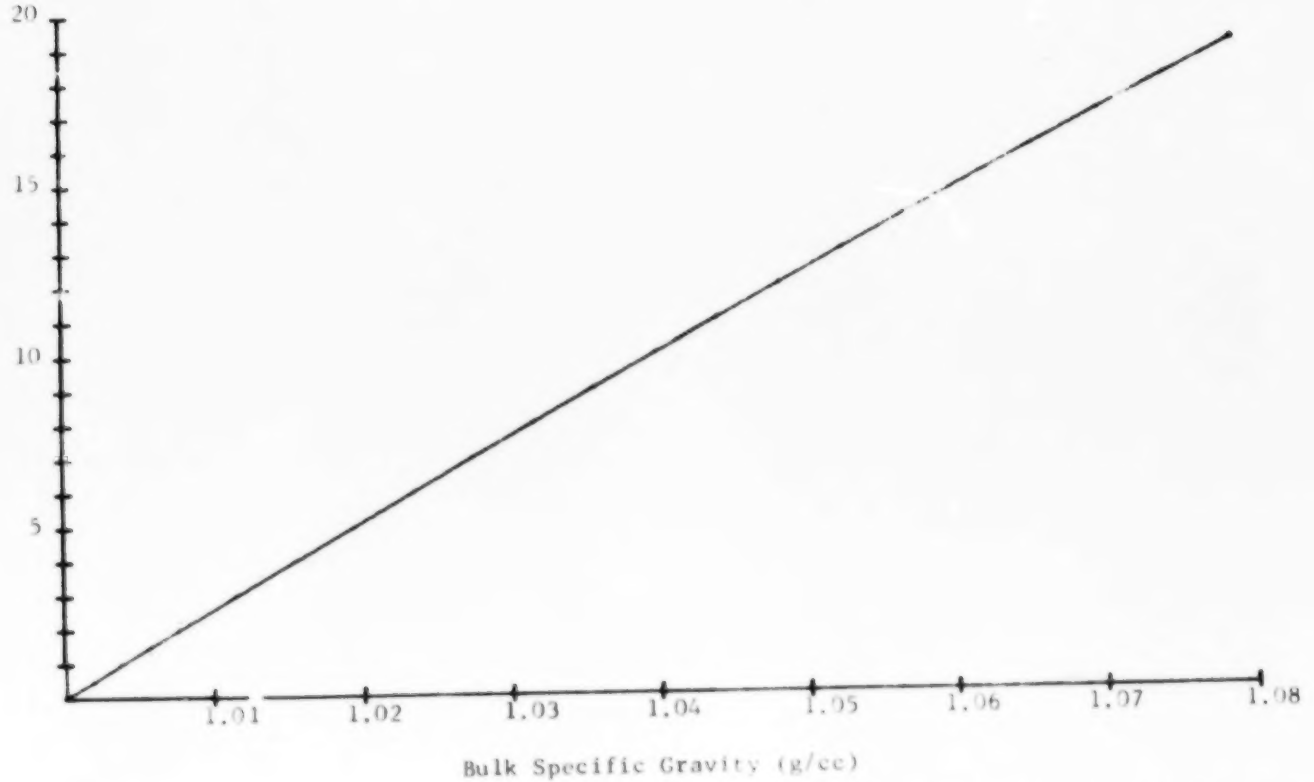
Results of Sedimentation rate grading curves; salinity of 28.9 ppt

TABLE 1

Region %	t_f Min.	v_f mm/sec	v_f ft/sec	t_d Min.
0-10	10	5.0	.016	62
10-20	15	3.5	.011	91
20-30	18	3.0	.0098	103
30-40	25	2.3	.0075	136
40-50	40	1.5	.0049	210
50-60	95	.75	.0026	428
60-70	450	.20	.00066	1713
70-100	1000	.10	.00033	3525

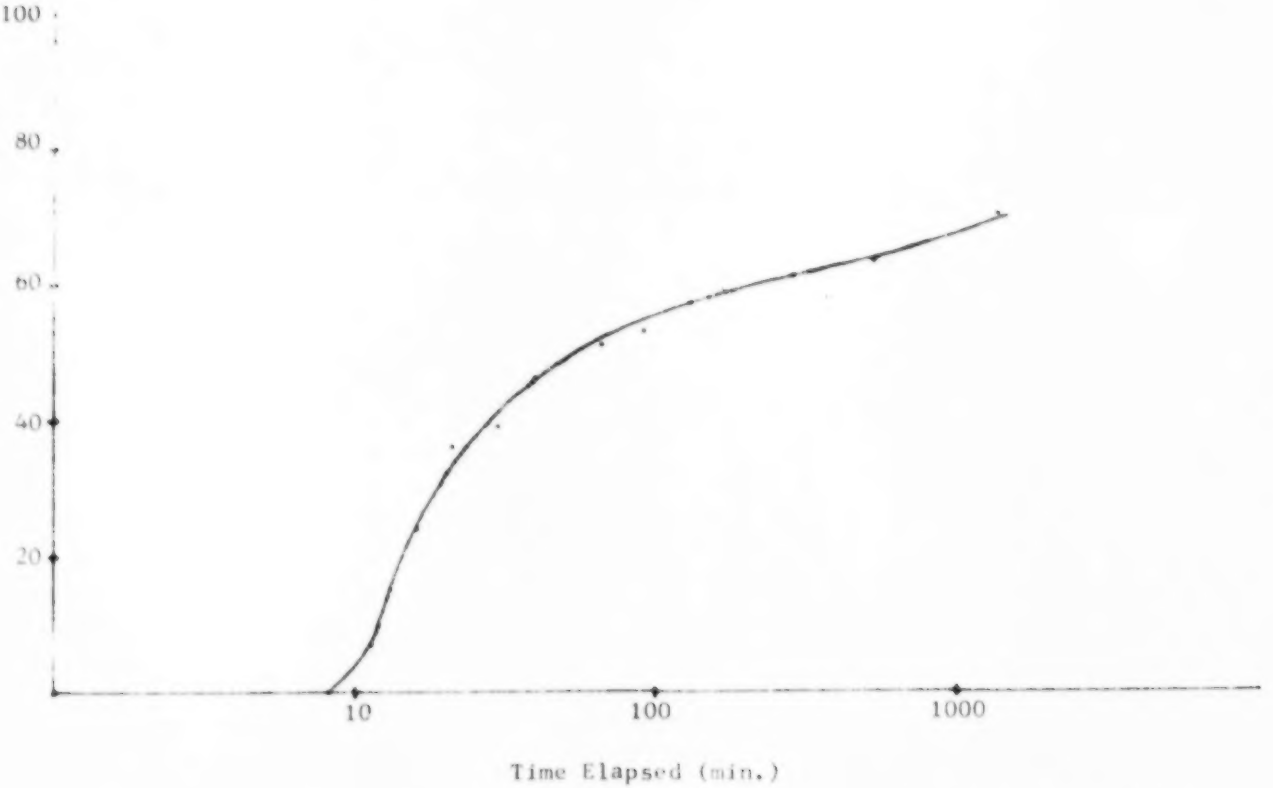
t_d calculated from t_f and v_f extrapolated from figures II and V. t_f, v_f, and t_d determined for median of each region.

TABLE II



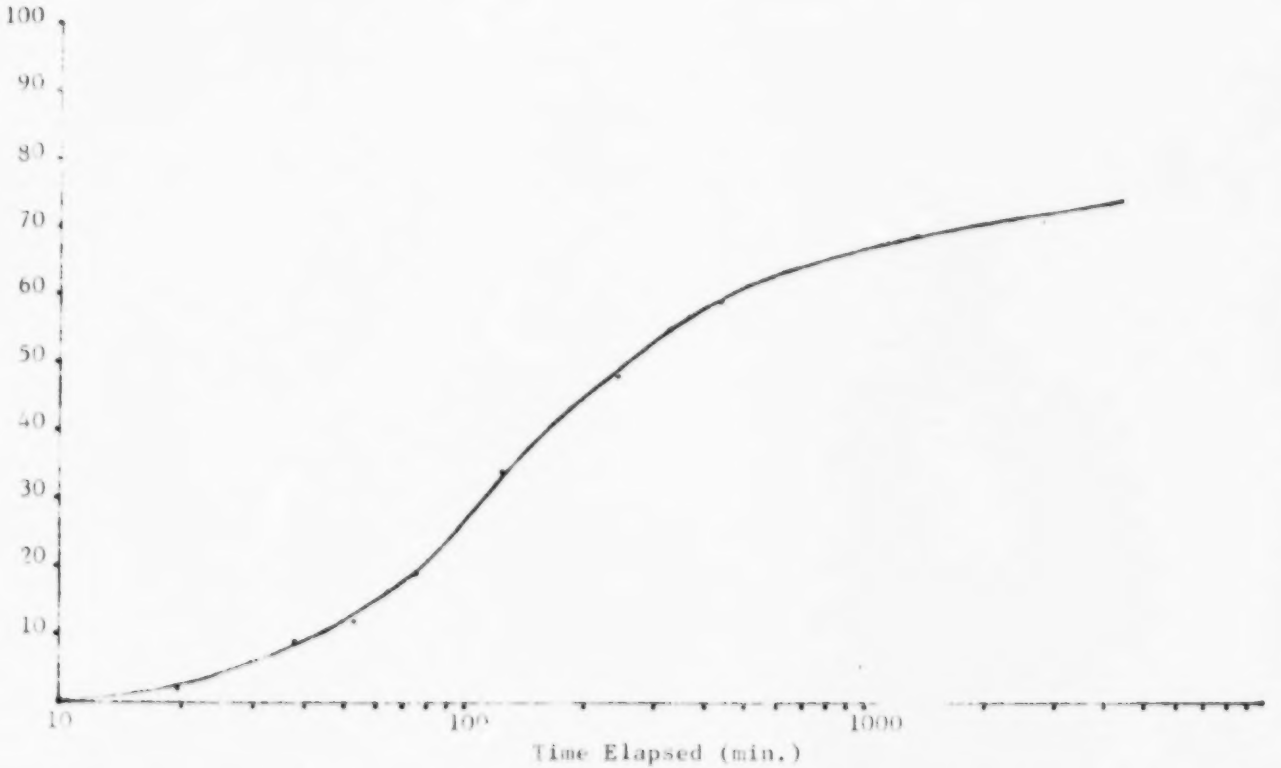
Correalation between bulk specific gravity and the percentage of solids for sludge with solids ℘ = 1.62 and liquid phase ℘ = 1.000

Figure I



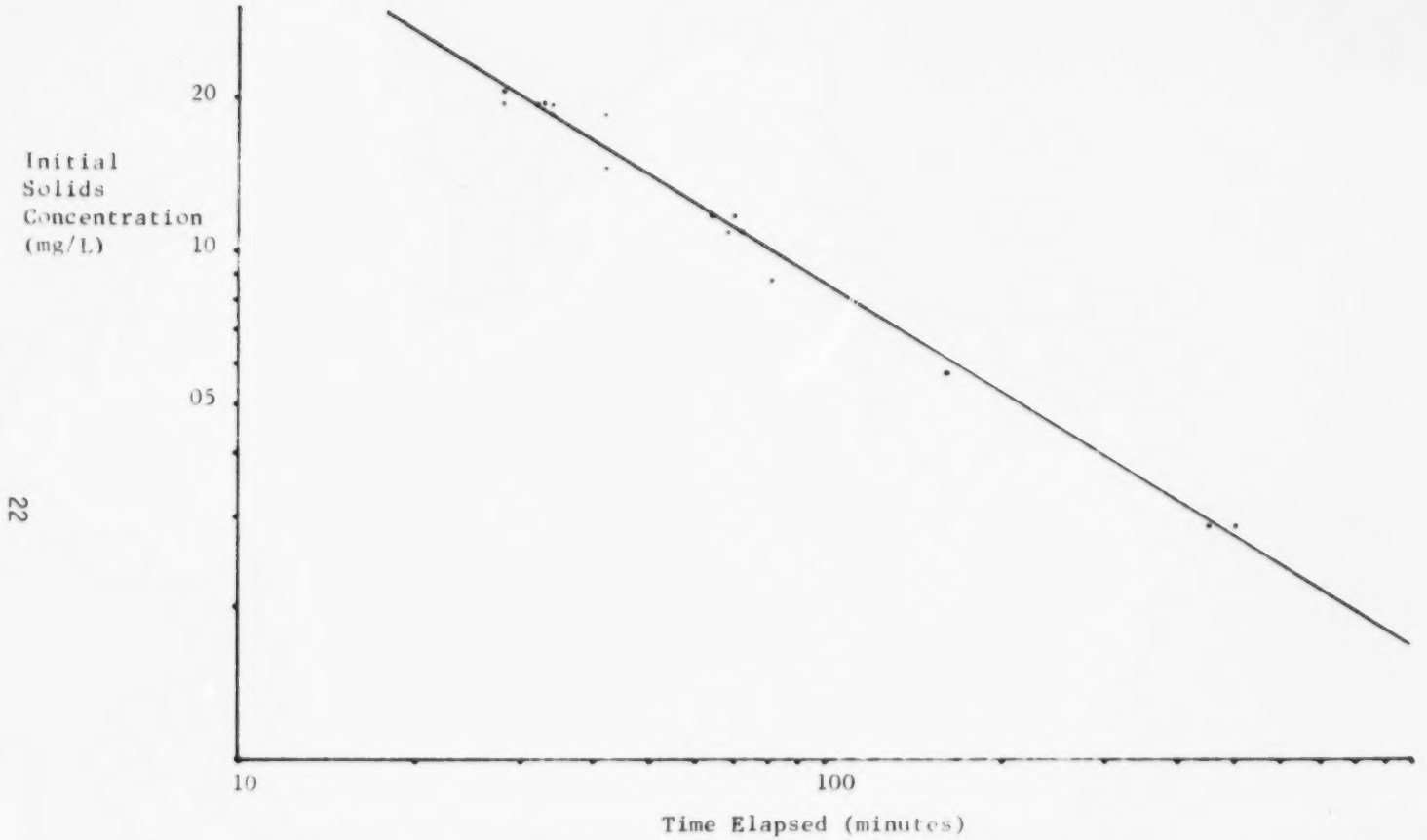
Sedimentation grading curve, initial suspended solids concentration of 197 mg/L

Figure 11



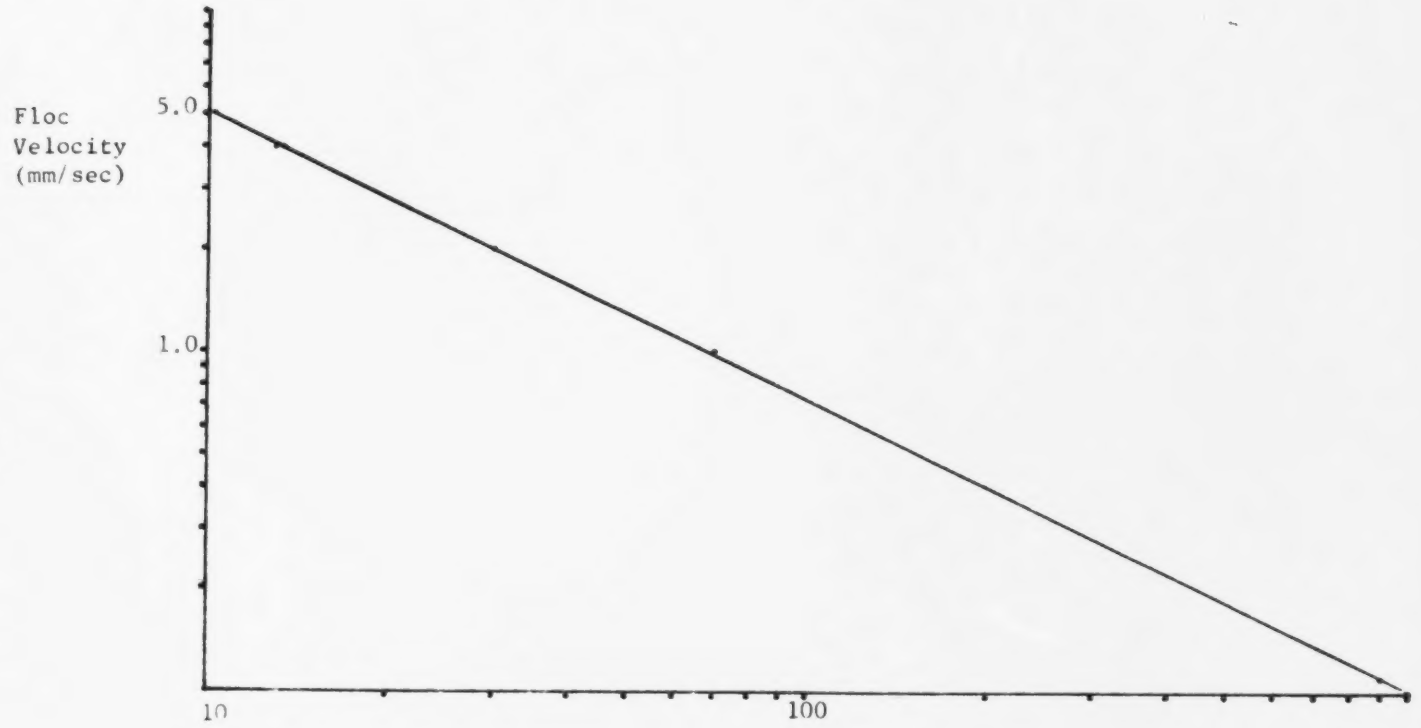
Sedimentation grading curve, initial suspended solids concentration of 58 mg/L

Figure III



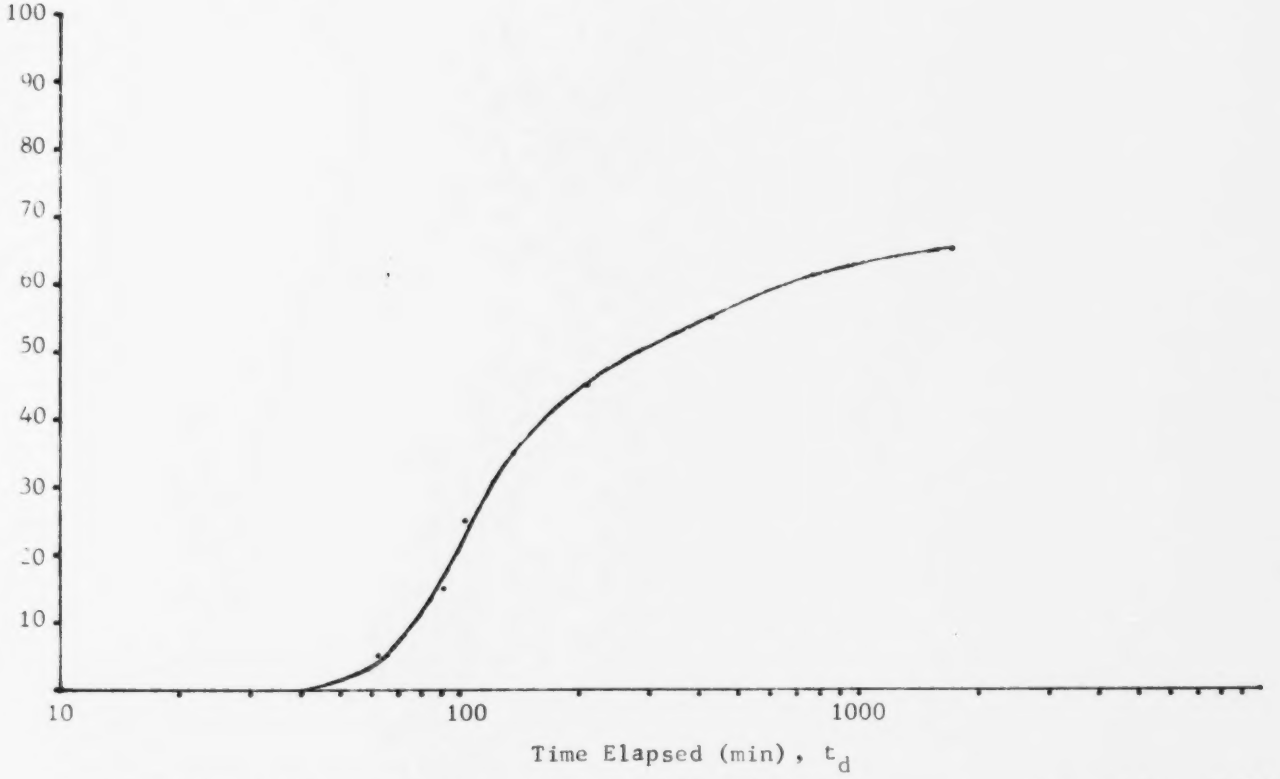
Time for 40% of solids to settle as a function of initial suspended solids concentration Constructed from Table I.

Figure IV



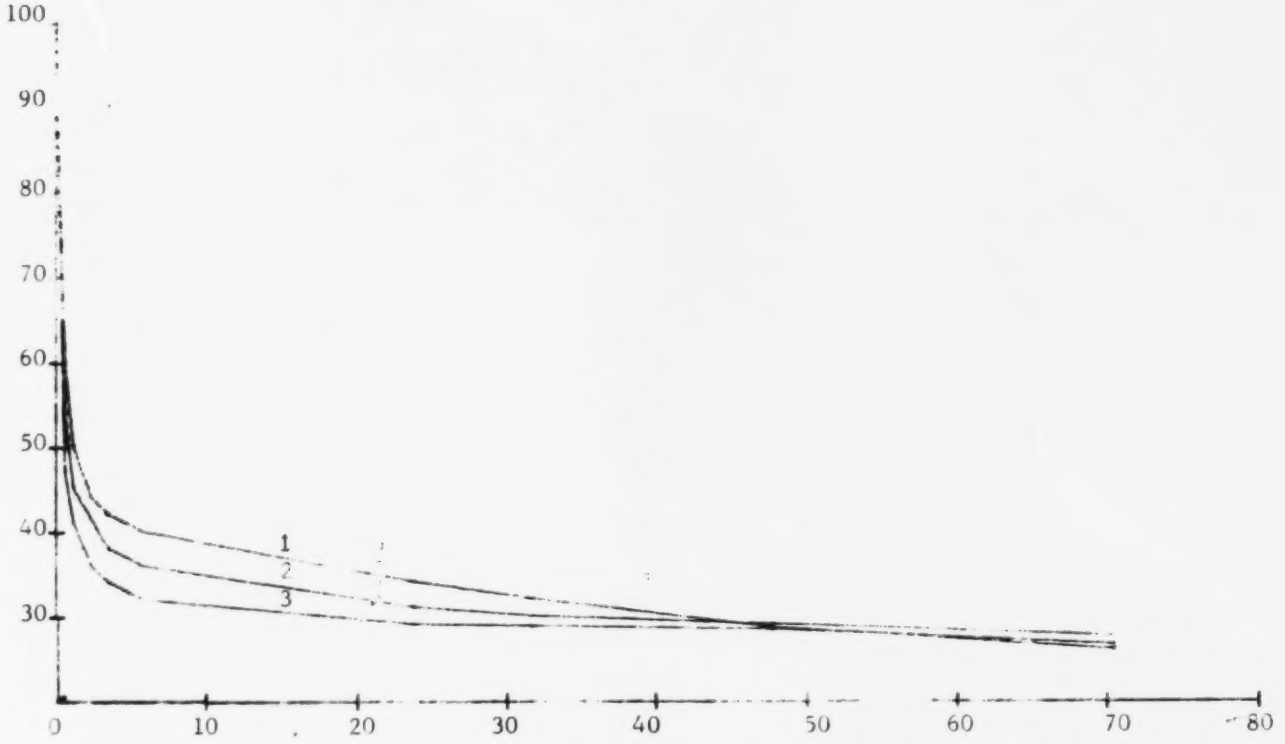
Settling velocity of discrete flocs as a function of time. Initial suspend solids concentration was 197 mg/L. Velocity determined by timing flocs over a .5 metre interval.

Figure V



Time recuired for bottom deposition with 197 mg/l solids concentration and h = 15.24 metres

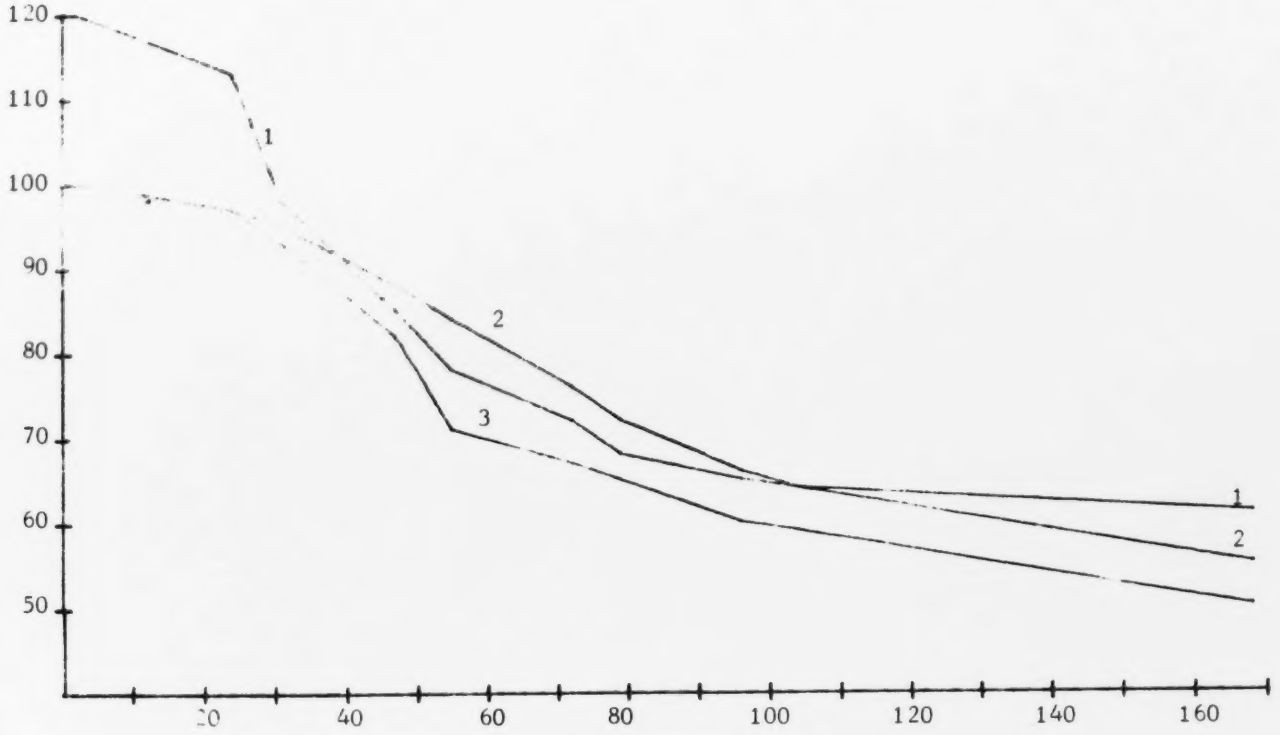
Figure VI



Effect of CaO on the gravity thickening of sludge initial solids concentration .8%

1. 0 g/L CaO
2. .39 g/L CaO
3. 1.43 g/L CaO

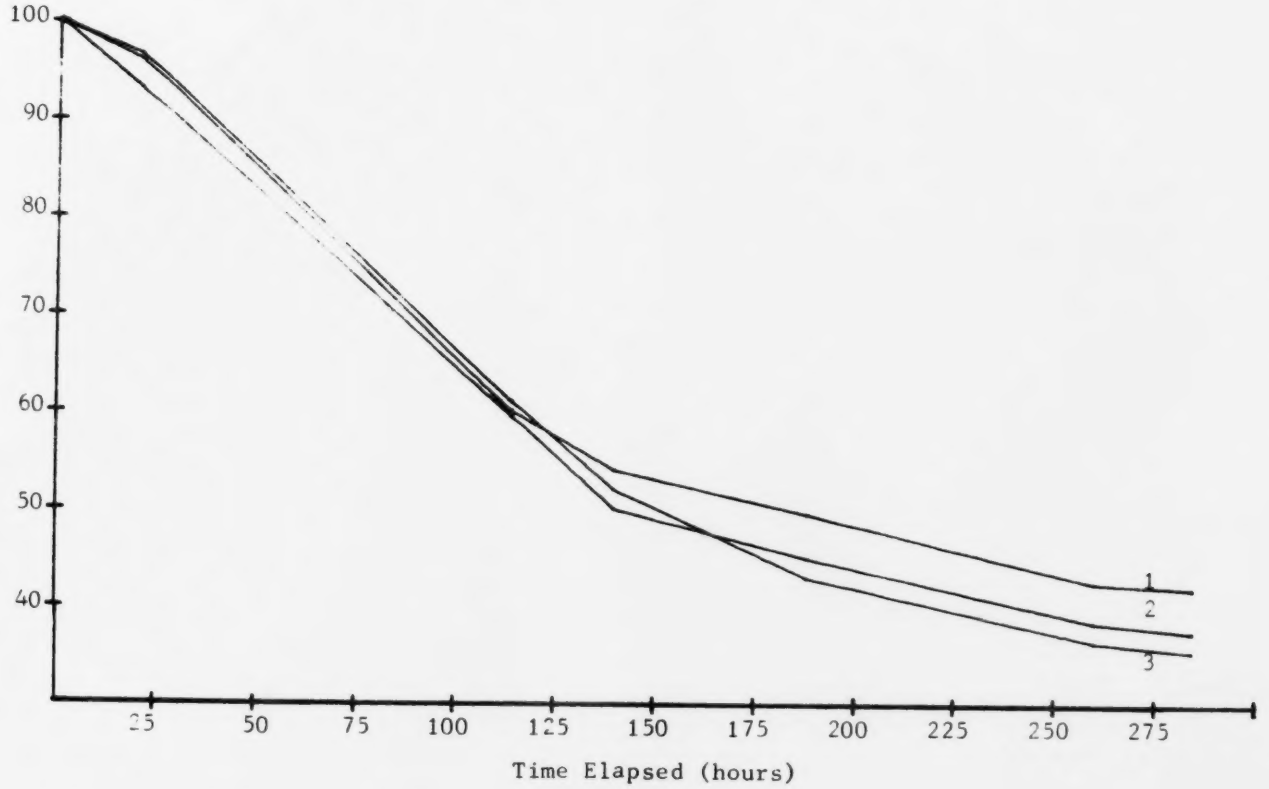
Figure VII



Effect of additives on the gravity thickening of sludge initial solid concentration 2.2%

1. 32 g/L NaCl
2. 20% Seawater by Volume
3. Control

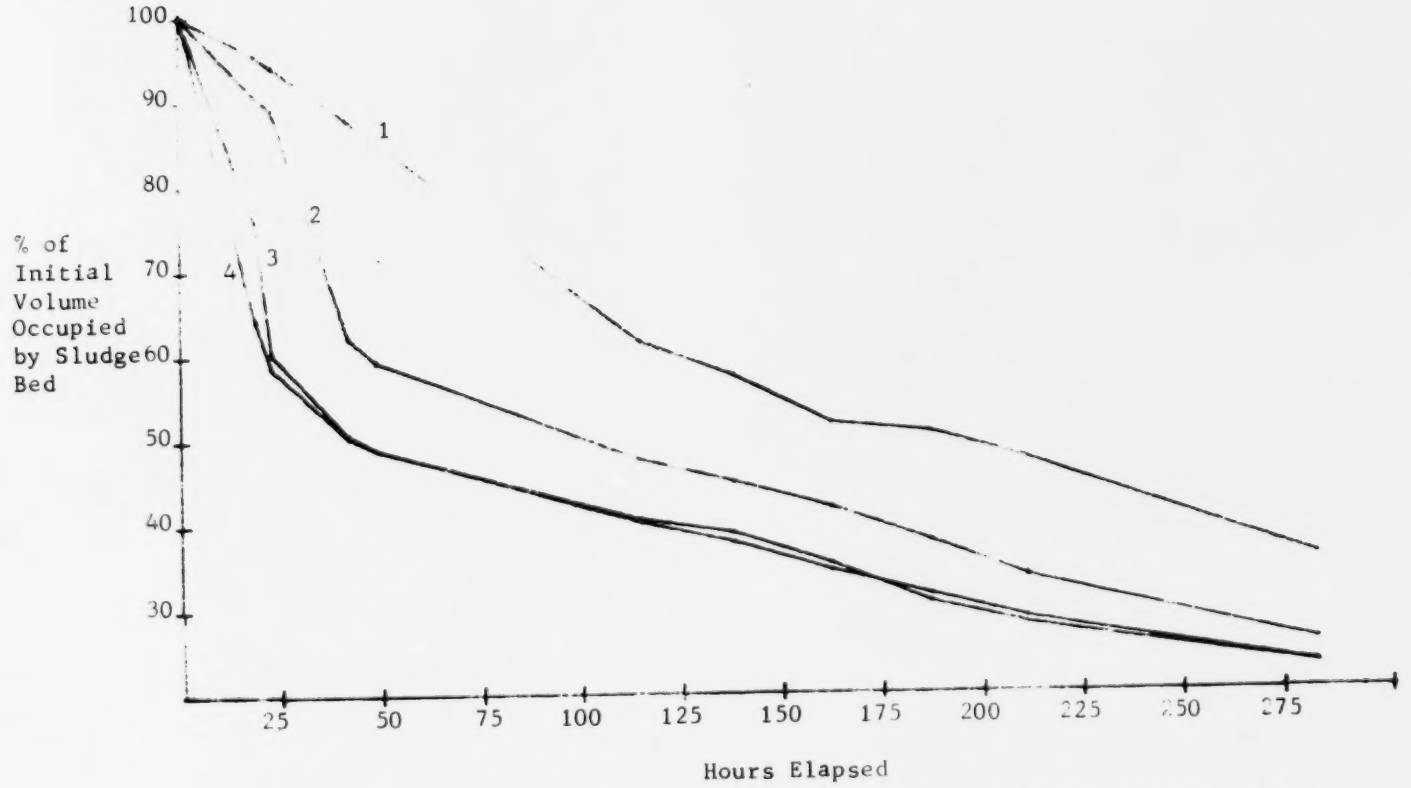
Figure VIII



Effect of $FeCl_3$ $6H_2O$ on the gravity thickening of sludge initial solids concentration 2.2%

1. 50 mg/L
2. 400 mg/L
3. 0 mg/L

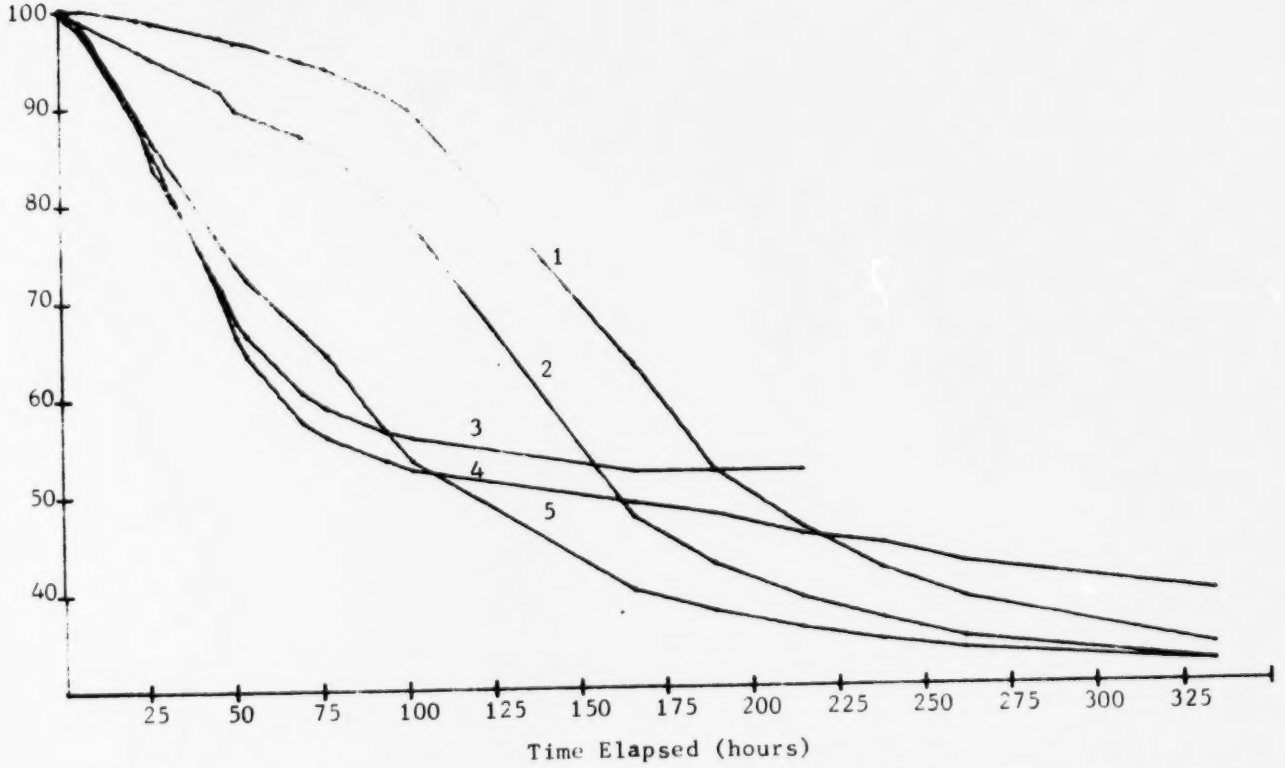
Figure IX



Effect of $Al_2(SO_4)_3\ 14(H_2O)$ on the gravity thickening of sludge initial solids concentration 1.15%

1. 200 mg/L alum
2. 50 mg/L alum
3. 100 mg/L alum
4. 0 mg/L alum

Figure X



Effect of $Al_2 (SO_4)_3 \ 14H_2O$ on the gravity thickening of sludge initial solids concentration 1.78%

1. 0 mg/L
2. 25 mg/L
3. 300 mg/L
4. 150 mg/L
5. 50 mg/L

Figure XI

This intern report was read and accepted by a staff member at:

Agency: National Environmental Research Center

Address: Pacific Northwest Environmental Research Laboratory
Corvallis, Oregon 97365

This report was completed by a WICHE intern. This intern's project was part of the Resources Development Internship Program administered by the Western Interstate Commission for Higher Education (WICHE).

The purpose of the internship program is to bring organizations involved in community and economic development, environmental problems and the humanities together with institutuions of higher education and their students in the West for the benefit of all.

For these organizations, the intern program provides the problem-solving talents of student manpower while making the resources of universities and colleges more available. For institutions of higher education, the program provides relevant field education for their students while building their capacity for problem-solving.

WICHE is an organization in the West uniquely suited for sponsoring such a program. It is an interstate agency formed by the thirteen western states for the specific purpose of relating the resources of higher education to the needs of western citizens. WICHE has been concerned with a broad range of community needs in the West for some time, insofar as they bear directly on the well-being of western peoples and the future of higher education in the West. WICHE feels that the internship program is one method for meeting its obligations within the thirteen western states. In its efforts to achieve these objectives, WICHE appreciates having received the generous support and assistance of the Economic Development Administration; the Jessie Smith Noyes Foundation; the National Endowment for the Humanities; the National Science Foundation; the Division of Education of HEW; and of innumerable local leaders and community organizations, including the agency that sponsored this intern project.

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